

ATLAS RELIABILITY ANALYSIS

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Key elements of the 36 MJ Atlas capacitor bank have been evaluated for individual probabilities of failure. These have been combined to estimate system reliability which is to be greater than 95% on each experimental shot. This analysis utilizes Weibull or Weibull-like distributions with increasing probability of failure with the number of shots. For transmission line insulation, a minimum thickness is obtained and for the railgaps, a method for obtaining a maintenance interval from forthcoming life tests is suggested.

Introduction

The Atlas machine is to operate with 95% reliability. This means that on 95% of the events in which current is applied to a load (i.e. the load is damaged), the high voltage system will not either prefire or breakdown. This definition focuses on events which can lead to the loss of a load package and the loss of the investment in load diagnostic setup. Moreover, this definition excludes issues associated with the bank charging system. Since the charge system operates on a sufficiently slow time scale it is actively monitored and a failure in the charge system will lead to an abort with no current applied to the load. Note that this is not the same as 95% availability—there may be occasions when a shot will be delayed a short time while problems detected in pre-shot tests (e.g. trigger-system test shots) are dealt with. In the failure probability calculations below, the Weibull distribution (see the Appendix) is utilized. This distribution function is frequently used for electronic components which have a probability of failure which initially increases with shot count. The hazard rate, $h(n)$, is the conditional probability of failure, or the probability that shot n fails given that $n-1$ successful shots have preceded the n th shot, and is given by $P(n)/1-F(n)$ where $P(n)$ is the probability density function given by $F'(n)$, and $F(n)$ is the distribution function of the number of shots to failure. The Weibull distribution has a particularly simple form for the hazard rate: $h(n) = (k/n)(n/n)^{k-1}$ where n is the characteristic life. In the region where $F(n) \ll 1$, the hazard rate is approximately the same as the probability density function. This is the case for component hazard rates in many-component systems where typically the individual probabilities of failure are very small in order to have an acceptable failure probability for the entire system. Atlas has four major high voltage areas of reliability concern: (1) the trigger system, (2) the transmission line insulation, (3) the capacitors, and (4) the rail gaps. Other components, such as the series and shunt resistors, will not be addressed in the following reliability analysis since they will be sufficiently conservatively designed. Some elements of the system will be replaced or refurbished on each shot (e.g. vacuum insulator). The total reliability budget is equal to 5% failure rate per shot. Where possible, this is estimated from test data. The following analysis does not include infant mortality. This issue will be handled on Atlas by component and sub-system pre-tests. This testing is greatly facilitated by the Atlas circuit which permits test firing each of the 20 Marx units individually. (The test load is the parallel combination of the shunt resistors in the other 19 modules). In the case of the rail gaps, operational data and maintenance procedures are cited to justify the reliability estimate.

I. Trigger system reliability

The trigger system for Atlas is sufficiently low energy that trigger tests can be made prior to each shot. These tests will monitor key electrical parameters (e.g. voltage on the pulse charge capacitors) and photographically monitor the trigger-pulse streamers in each of the Atlas gaps. The problems that can lead to an Atlas misfire are associated with weak trigger system output: (a) prefires of the trigger gaps or (b) failure or degradation of a trigger system component such as a cable or capacitor. A weak trigger output will result in failure-to-multi-channel in the trigger system railgaps which are identical to the Atlas Marx railgaps. Rail gap reliability will be discussed in Section IV (below). Low-coulomb operation of the trigger system rail gaps is expected to greatly improve their reliability. In addition, the low number of trigger-system rail gaps, 20 vs. 300 in the Atlas Marx sections, and the ability to run comprehensive trigger test(s) prior to each shot makes this part of the Atlas system a negligible factor in the reliability analysis.

II. Transmission Line Insulation

The transmission line insulation is made from layers of .005" Mylar. The entire line is considered to extend vertically from the bottom of the Marx sections to the outboard edge of the rectangular, "disk" transmission line and to the inboard edge of the transmission line where the vacuum insulator and load region are located. The insulation thickness is treated as constant in this analysis, although one Atlas Marx design variant has tapered insulation thickness for constant electric field stress in the vertical, Marx portion of the transmission line. The maximum constant electric field occurs at the top of the Marx near the shunt resistor and the input to the radial transmission line. The voltage at this point, based on circuit simulations, is ~ 400 kV for a 600 kV equivalent voltage on the Marx (max. operating voltage for Atlas), because of voltage division by the internal inductance of the Marx and the series and shunt damping resistors. The insulation thickness proposed for the Atlas baseline design is 0.8 cm to 1.0

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cm. Life calculations of the Mylar transmission line insulation may indicate that the Mylar requires replacement a few times during the 1000 shot design life of Atlas. The cost of re-insulating with fresh Mylar is moderate in terms of material, manpower and Atlas down-time. The data used to evaluate the Atlas transmission insulation is contained in two articles in "Pulsed Electrical Power Dielectric Strength Notes PEP 5-1"^{1,2}. The scaling of shot life as a function of the ratio of single-shot breakdown field to the applied field for several different volumes of mylar is given in Reference 1. The scaling of breakdown field with volume is conservatively taken to be $\text{Volume}^{-.092}$ from a fit to the data. The scaling of the median number of shots to failure, \bar{N} , is given by:²

$$\bar{N} = (E \text{ median for failure @ 1 shot} / E \text{ operating})^{7.5} \quad \text{II. 1}$$

Utilizing the volume scaling of single shot failure, the median shot life is:¹

$$\bar{N} = [(3.95 \text{ MV/cm} / E \text{ operating}) \times (3 \text{ cm}^3 / \text{Insulation Volume})^{.092}]^{7.5} \quad \text{II. 2}$$

The 1000 shot machine life at full operating voltage can be achieved with an insulation thickness of 0.9 cm. At 0.8 cm thickness, the mean life of the mylar insulation is long enough to require one replacement during the 10 year machine life. The data in Reference 2 can be used as a set to estimate the probability of failure on a per-shot basis. This can approximately be done by scaling each data point, by the expression given above, to the electric field required to give $\bar{N}=1000$ for the Atlas insulation volume. The scatter in the data provides the information required to plot $F(n)$ given in Table 1.

<u>Estimated Effective shot count at failure</u>	<u>Incremental # of Failure Events</u>	<u>F</u>
620	1	.0833
715	1	.1667
900	2	.3333
970	1	.4167
1000	2	.5833
1100	1	.6667
1160	1	.7500
1200	1	.8333
1700	1	.9167
1800	1	1.000

Table 1: Scaled shot count at failure for 12 data points from Ref. 2

This data set is shown in Figure 1. The dashed curve is a Weibull distribution (See Appendix) with a k of 4.65 and a \bar{n} of 1062, which closely fits the observed data of from Reference 2. The conditional probability of failure on a given shot (hazard rate) is given by $h(n) = (k / \bar{n}) (n / \bar{n})^{k-1}$. For an Atlas insulation system designed for a life of ~1000 shots, the probability of failure during the 1000th shot is .352%. Note: the total, integrated probability of an insulation failure on or before the 1000th shot is ~50%. The hazard rate at the design life for 0.8 cm thick mylar insulation ($\bar{n} \sim 500$) can be estimated approximately by scaling by the median number of shots to failure:

$$h_{0.8\text{cm}}(n=500) \sim \bar{n}_{0.9\text{cm}} / \bar{n}_{0.8\text{cm}} \times h_{0.9\text{cm}}(n=1000) \quad \text{II. 3}$$

Since $\bar{n}_{0.9\text{cm}} / \bar{n}_{0.8\text{cm}} \sim 2$, the 0.8cm mylar's hazard rate near the 500th shot is ~0.7%. An 0.8 cm thick mylar insulation system (allowing for a change of insulation after ~ 5 years of operation) or a 0.9 cm mylar insulation system with a mean life of 1000 shots have failure probabilities which do not significantly impact the overall budget of 5.0% probability of failure per shot. The 0.9 cm thick mylar insulation has ~0.5 nH increase in inductance with respect to the 0.8 cm thick mylar insulation pack. The total system inductance is ~28 nH.

III. Capacitor Reliability

Maxwell Laboratories has supplied derived life data for two capacitor designs which meet the Atlas electrical requirements. The design data used are proprietary, but F-functions for individual capacitors are given below as estimated from the Maxwell data in the range where $F \leq 0.1$. The derived data take into consideration the shot time-scale, 60 kV operating voltage, energy storage, 15% voltage reversal and packaging constraints of Atlas. Both cases are conservative, and for slow charge rates.

Design A F individual ~ $0.1(n/1600)^{2.3}$, Half life individual ~ 3600 shots

Design B F individual ~ $0.1(n/2800)^3$, Half life individual ~ 5200 shots

The probability of failure of an individual capacitor at shot n , $P_f(n)$, is given by: $P_f(n) = \partial F_f(n) / \partial n$. The individual probability of survival at shot n is given by: $P_f^{\text{Success}}(n) = 1 - P_f(n)$. The probability of success for the Atlas capacitor bank of 1200 capacitors at shot n , $P_{\text{bank}}^{\text{success}}$, is given by

$$P_{\text{bank}}^{\text{success}}(n) = (P_f^{\text{Success}}(n))^{1200} = (1 - P_f(n))^{1200}$$

TABLE II below gives $P_{\text{bank}}^{\text{success}}(n)$ for both cases for several shot counts.

Shot #	Design A:	Design B:
246	98.5%	99.9%
365	97.5%	99.8%
630	95%	99.35%
1000	91%	98.37%

Table II: Probability of Success on Each Shot for Two Maxwell Capacitor Designs

Design B for Atlas capacitor clearly satisfies the 95% reliability requirements with sufficient margin for other component reliability requirements. Without additional testing of design A to relax Maxwell's conservative scaling, design A would require a complete change of capacitors two times after commissioning at the 97.5% reliability level.

IV. Rail gap reliability

Two reliability issues for the multi-channel rail gaps as used for the 300 Atlas Marx-bank switches are single channeling and prefire.

IV. a. Single Channel Occurrence in a Spark-gap

The Atlas design is tolerant of single channeling by a small number of the rail gaps. This is not considered to be a system failure that causes the loss of a shot or unnecessarily destroys a load. Open shutter cameras will be used to identify gaps which single-channel for replacement or maintenance prior to the next shot. This is necessary, since single-channel operation can lead to enhanced prefire probability on subsequent shots due to local damage to the switch rails and increased debris on the insulator surfaces³. Maxwell Laboratories, Inc. has developed an improved version of their standard rail gap which has been designed and tested to withstand up to 1.2 MA and 5 coulombs in a single channel. Since the Atlas railgaps will operate at currents limited by the circuit design to ~ 450kA per spark gap and a charge transfer of ~ 2.2 coulombs per spark gap, this variant of the Maxwell railgap is expected to provide a durable, maintainable switch that is tolerant of the single-channel fault mode.

IV.b. Prefires

According to Maxwell Laboratories a prefire has never been observed on the first occasion of stressing a fresh switch, leading to the conclusion that the prefire is induced by cumulative damage of a number of shots.³ The static breakdown of a fresh 120kV switch is ~ 180 kV at the standard fill gas pressure. This is consistent with the performance of the IDNB facility at Los Alamos which has achieved >3000 shots on each of four rail gaps operated at very low charge transfer (~.09C/shot/rail gap) and current (~30kA/shot/rail gap). This suggests that a maintenance program can achieve a low prefire rate in the Atlas Marx rail gaps by frequently restoring the rails and the trigger-to-rail insulator surfaces to new conditions. In the following, the maintenance interval is discussed. The Maxwell improved rail gap achieved ~ 100 shots to the first prefire at 120 kV operation with a charge transfer and current similar to the Atlas requirement. The sixty cylindrical rail gaps on the Staged Theta Pinch Experiment at Los Alamos, distant ancestors of the Maxwell rail gap, achieved ~ 300 shots at 120 kV, at a current transfer >1.5 coulombs, and another 2000 shots at 80 to 100 kV all without prefire. Shiva Star, with 144 rail gaps, has fired ~ 100 shots at ~ 85kV with a system prefire rate estimated to be ~ 5%⁴ — some of the prefires maybe due to the trigger system. The recent Marauder experiments, using a subset of Shiva Star, have achieved ~ 600 shots with 12 gaps at 80 kV without a prefire due to the rail gaps. (Several have occurred from other causes). Additional improvement can be obtained with non-standard fill gas at high pressure. This is made possible by the high voltage trigger system to be used on Atlas.

Experience at the SHIVA Star Facility of Phillips Laboratory suggests reconditioning Maxwell rail gaps after every 100 coulombs of normal operation.⁴ At the Atlas operating conditions ~ 40 shots are required to reach the 100 Coulomb maintenance interval. This indicates that routine maintenance of each gap on a 20 to 40 shot interval can achieve a prefire rate consistent with the Atlas system reliability of > 95%, if all of the other recent improvements are utilized for the Atlas rail gaps. The exact maintenance interval will be determined by life testing a few gaps during Atlas construction, and by experience gained during Atlas operations. Gaps that are observed to single-channel will be refurbished as they are detected.

The allowed maximum system failure rate for the rail gaps must be < 3.02% when the other Atlas system elements are taken into account. The scope of the required life tests to determine the maintenance interval can be estimate by using the Weibull distribution (see the Appendix) along with the allowed maximum failure probability for the array of rail gaps and the shot count at the maintenance interval. The spark gap probability function is assumed to obey statistics similar to the capacitors with $F \sim n^k$ in the range $F \ll 1$ with $k \sim 2$ to 3. Hypothetical probability distribution functions for a single gap are given in Figure 2 for 20 and 40 shot maintenance intervals where the maximum probability of prefire, at the maintenance interval, is determined from the allowed maximum system prefire probability of 3.02% with a 300-gap system. For each assumed maintenance interval, probability distribution functions are shown with $k=2$ and $k=3$. Also shown in Figure 2 are data from the Maxwell tests on the improved rail gap and the Los Alamos experience with Staged Theta Pinch rail gaps. If the rail gap prefire probability fits one of the Weibull distributions shown in Figure 2, the mean life to be achieved on a sample set of Atlas rail gaps would be at least 200 to 300 shots. The minimum number of life test data points required for a valid distribution function is ~ 10. This sets the scale of the required rail gap life tests for Atlas.

V. Atlas Reliability Analysis Conclusions

The Atlas high voltage system budget to achieve the required 95% shot success rate (5% total failure rate) is given in Table III:

<u>Atlas element</u>	<u>Failure Rate</u>
Trigger System	-----
Mylar Transmissionline Insulation	< .35% to 0.7%
Capacitors	< 1.63%
Rail Gaps	< 3.02%

Table III: Atlas Reliability Budget

Trigger system reliability is achieved by test-firing the trigger system prior to each shot. Transmission line insulation and capacitor reliability are achieved by design based on published and proprietary test data. Achieving rail gap reliability requires a routine maintenance program with the maintenance interval based on life tests to be conducted on a sample of Atlas rail gaps. The expected maintenance interval is ~ 20 to 40 shots.

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Appendix: Probability of Failure Calculations

Weibull distribution: For many electrical components, a Weibull distribution of operations-to-failure is utilized. This is particularly appropriate when the failure rate initially increases as a power of the number of operations. The Weibull probability density function for failure of component (with a "threshold parameter" of zero) is given by A.1

$$P(n) = (k/\bar{n})(n/\bar{n})^{k-1} \exp \left[-\left(\frac{n}{\bar{n}} \right)^k \right] \quad (A.1)$$

Where \bar{n} is the characteristic life and n is the shot count. The distribution function, $F(n) = \int_0^n P(n)dn$, is given by A.2

$$F(n) = 1 - \exp \left[- \left(\frac{n}{\bar{n}} \right)^k \right] \quad (A.2)$$

The Weibull distribution function has a particularly simple form for the "hazard rate", $h(n)$, which is the conditional probability of failure at event n given that the previous $n-1$ shots were successful. The hazard rate is defined by A.3

$$h(n) = \frac{P(n)}{1 - F(n)} = \frac{F'(n)}{1 - F(n)} \quad (A.3)$$

For the Weibull distribution given above:

$$h(n) = \frac{k}{n} \left(\frac{n}{\bar{n}} \right)^{k-1} \quad (A.4)$$

Approximate probability functions: For most cases of interest for Atlas, $(n/\bar{n}) \ll 1$, since the failure probability required for individual components dictates that their characteristic life is much greater than the machine life or component maintenance interval. For example, the Maxwell capacitor data has $k \sim 2.3$ to 3.0 with $F(n) = 0.5$ at $n \sim 3600$ to 5200 vs. the 1000 shot life of Atlas. The reliability analysis for the rail gaps indicates that at a $k \sim 2$ to 3 , the maintenance interval is ~ 20 shots with $F(n) = 0.5$ at $n \sim 200$ to 500 . When $(n/\bar{n})^k \ll 1$ the approximate, power-law probability distributing functions used in sections III and IV are indistinguishable from the Weibull distribution. The Weibull distribution's hazard rate is also approximately the same as the probability density function in this same limit.

References

1. Pulsed Electrical Power Dielectric Strength Notes, PEP 5-1, AFWL TR 73-167: "Revision of Breakdown Data Concerning Mylar", Page 5-4, Ian D. Smith.
2. Pulsed Electrical Power Dielectric Strength Notes, PEP 5-1, AFWL TR 73-167, "Note 11, Pulse Life of Mylar", page 11-8, Figure 1, J. C. Martin
3. Richard Miller, Maxwell Laboratories, private communication.
4. J. Graham, Maxwell Laboratories, private communication.

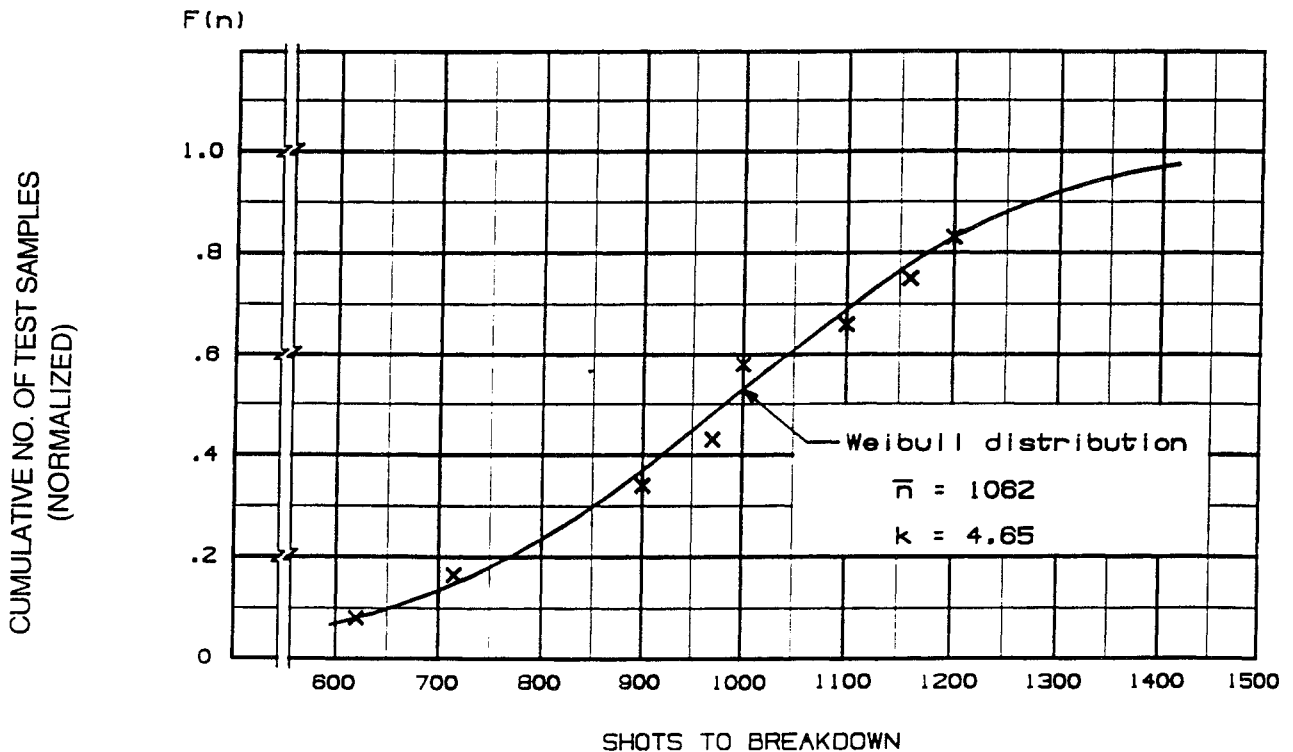


Figure 1: Weibull Distribution Fit to Mylar Breakdown Test Data^{1,2} - Data Scaled to Electric Field for a Mean Number of Shots to Breakdown of 1000.

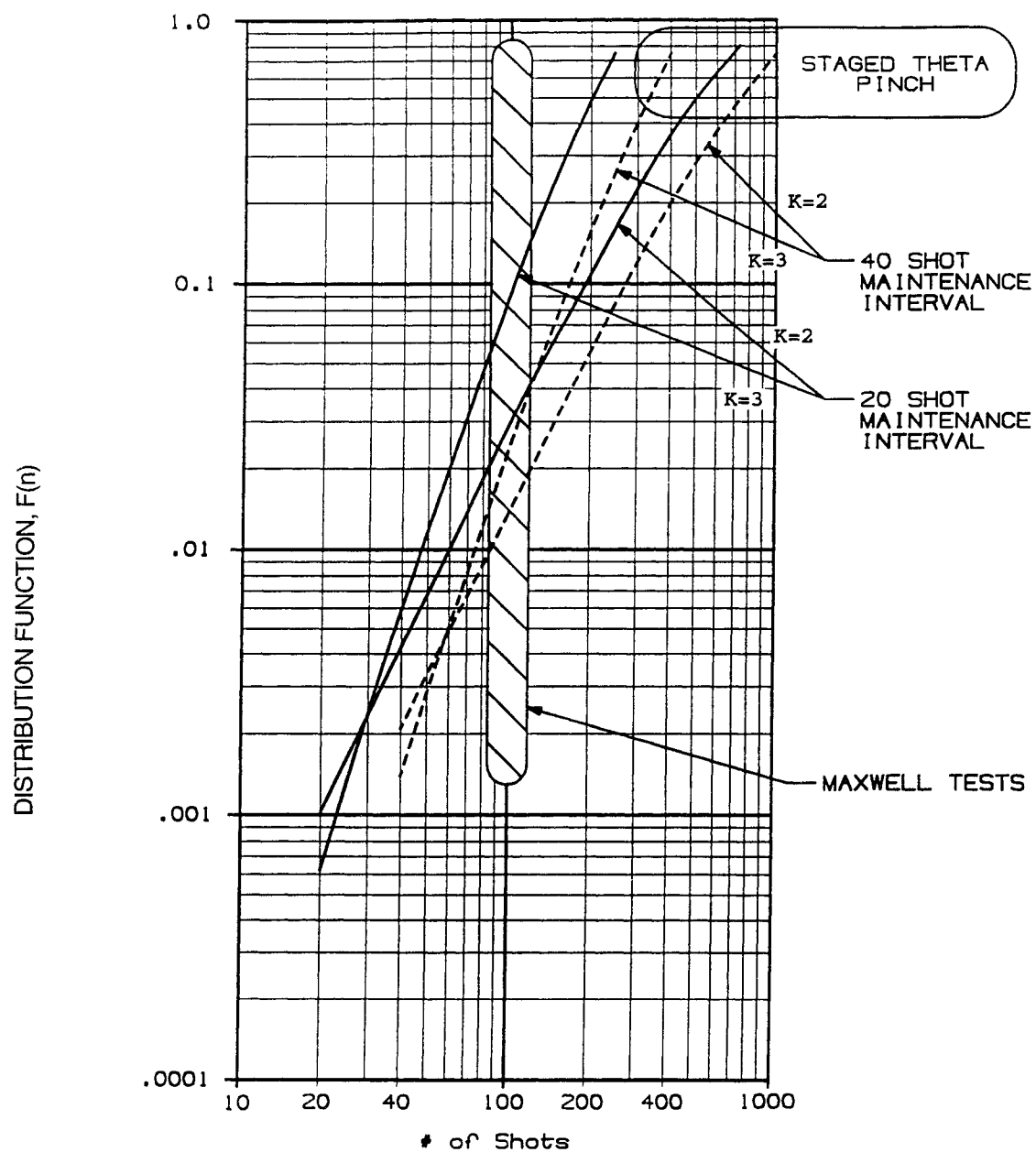


Figure 2: Required Single Gap Weibull Distributions to Meet Atlas Requirements (System prefire probability <3%)